THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 57, No. 6, July–August 1978
Printed in U.S.A.

Atlanta Fiber System Experiment:

Lightguide Cable Manufacture and Performance

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(Manuscript received December 5, 1977)

The manufacture of the optical fiber ribbons and the optical cable used in the Atlanta Fiber System Experiment is described. Yields and added loss in each step of cable manufacture and installation are covered, along with the bandwidth changes resulting from packaging the optical fibers in the lightguide cable. Mechanical performance in tension and in bending are also considered, as well as the thermal stability of cable performance.

I. INTRODUCTION

As part of the Bell Laboratories Atlanta Fiber System Experiment, a small, ruggedized, high-capacity, optical fiber cable was designed, manufactured, and characterized both optically and mechanically. After manufacture and evaluation of the fiber optic cable, it was installed in underground ducts, typical of those used by telephone companies, and characterized once again. In the present paper, we describe the optical fiber ribbon and cable designs used for the Atlanta Experiment and their performance results. In addition, the cable environmental performance is also discussed. These results provide initial indications of the manufacturability of the cable design, including yield information.

II. FABRICATION OF OPTICAL FIBER RIBBONS

In 1970, a proposal was made to put optical fibers together into easily handled units for optical communication purposes.[1] This proposal suggested "the use of fiber ribbons consisting of linear arrays of fibers embedded in a thin, flexible supporting medium as components of a cable for fiber transmission systems." Such a medium is attractive from the splicing standpoint, since groups of fibers can be handled at once with relaxed alignment requirements needed to accomplish mass field

splicing.[2] Moreover, this linear array provides increased size and mechanical support, thereby improving the human handling qualities of the fibers.

Optical fibers can be assembled into a linear array structure in many different ways. The method chosen here was to sandwich 12 optical fibers between two layers of polyester-backed adhesive (adhesive sandwich ribbon, ASR).[3] The machine for making the ASR is described in Ref. 3. Figure 1 shows a sketch of the completed ribbon cross section. Each of the ASRs contained twelve Western Electric optical fibers which were coated in-line with ethylene-vinyl-acetate and proof-tested at 207 MN/m^2 (30 ksi). The fibers[4] supplied by Western Electric for the Atlanta Experiment were germania-doped borosilicate, multimode, graded-index, and were made using a modified chemical vapor deposition process (MCVD).[5] The ASRs manufactured using these fibers were then incorporated into the optical fiber cable for the Atlanta Fiber System Experiment.[6,7]

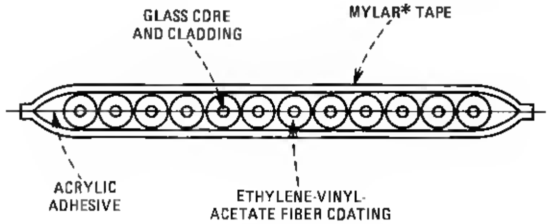

Fig. 1—Ribbon cross section.

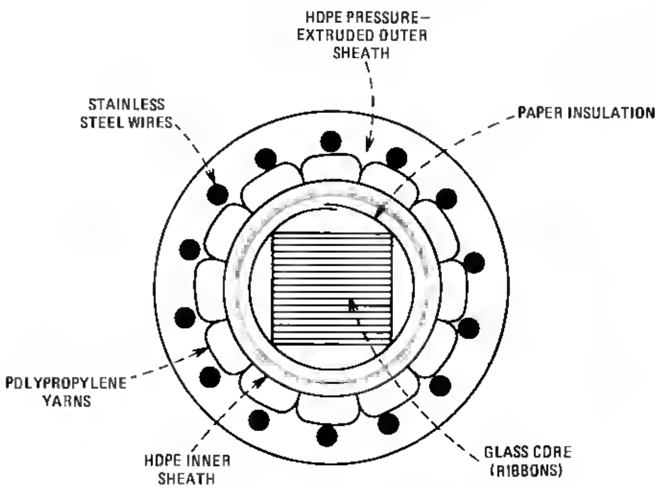

Fig. 2—Optical cable cross section.

* Registered trademark of E. I. DuPont de Nemours and Company.

Since the coated fibers are contiguous within the ribbon, any roughness in the coating results in microbending,[8] which increases the fiber loss. Indeed, it was found that this added loss due to microbending was essentially eliminated when the coated fibers were not contiguous within the ribbon. With contiguous fibers, increased pressure from the compliant rollers in the ribbon machine pushes the fibers together. It was found that, by adjusting this pressure, the added loss in the ribbon could be varied in certain coated fibers from about 1 to 19 dB/km.

A total of 16 ASRs, all approximately 1050 m in length, were made by Bell Laboratories. Four of the ribbons were discarded because of multiple fiber breaks. The 12 ASRs selected for the optical cable had a total of seven fiber breaks. Since that time, better fiber-winding techniques and improved ribbon machine design have substantially reduced the number of fiber breaks occurring during ribbon fabrication.

III. FABRICATION OF OPTICAL FIBER CABLE

The major consideration in the Bell Laboratories optical fiber cahle design was the simplification of the difficult task of splicing the optical fibers. This provided the motivation for selecting a cable design based on linear array fiber ribbons.

Figure 2 shows a developed view of the fiber optic cable design used for the Atlanta Experiment. The cable core consisted of 12 ASRs (each containing 12 fibers) stacked in a rectangular array to facilitate the application of factory-applied cable connectors. This stacked ribbon core was twisted into a helix with about a 15-cm lay, to improve the cable bending characteristics. A paper thermal insulation layer was longitudinally applied over the core, and a high density polyethylene (HDPE) inner jacket was extruded over the paper layer. This loosely fitting jacket provides enough space for the glass core to move, and thus allows relaxation of manufacturing and installation-induced stresses that otherwise could result in optical fiber breakage or excessive microbending loss.[8]

The reinforced outer sheath consists of helically applied strands of fibrillated polypropylene twine which provide thermal and mechanical isolation. The cable load-bearing strength members are helically applied stainless steel wires over which an HDPE outer sheath is pressure ex-

Table I — Mechanical data for the cable components

Cable Component	Tensile Stiffness (N/percent)
Glass (144 fibers)	934
Mylar (12 ribbons)	40
HDPE (inner jacket)	56
Polypropylene twine	209
Steel wire	2732
HDPE (outer sheath)	109

truded. This outer sheath provides chemical as well as mechanical protection for the entire structure. Table I contains a listing of the cable components and their respective material and cable assembly properties. Optical and mechanical performance results for this cable design are discussed in the following sections.

IV. OPTICAL PERFORMANCE

Optical fibers are incorporated in protective coatings, ribbons, and cables for protection during handling and installation. However, during this packaging process, microscopic perturbations of the fiber axis from straightness[9] can cause mode coupling, and thus add loss (microbending loss),[8] and reduce pulse delay distortion.[10] For our particular fiber design, coupling between guided modes and lossy radiation modes occurs when the fiber's longitudinal axis is deformed with periods of the order of 1 mm and amplitudes as small as a micrometer. Field-worthy cables must inhibit fiber axis deflections of this microscopic nature and yet allow for normal installation and handling procedures.

In this section, we discuss the optical transmission performance and the yield after each cable manufacturing step.

4.1 Transmission loss

The transmission loss versus wavelength characteristic of each unpackaged fiber was measured using an incoherent source and seven filters between 0.63 and 1.05 μm.[11] In addition, since in this wavelength region the added loss due to microbends is essentially independent of wavelength,[8] the added losses induced by packaging the fibers in ribbons and

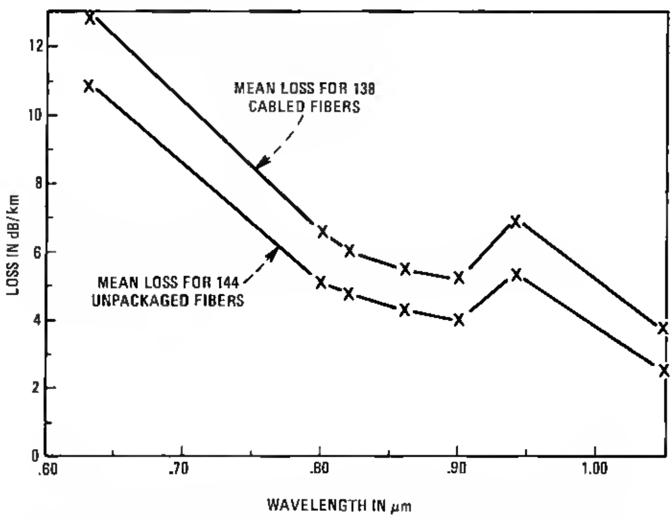

Fig. 3—Spectral loss before and after cable manufacture.

cables were measured using a He-Ne laser source. The use of 0.63-μm coherent radiation to measure packaging-induced loss provided the capability of visually locating and diagnosing high scattering loss regions in the packaged fibers. These two loss measuring sets had their launch optics adjusted to match the average 0.23 numerical aperture of the Western Electric fibers. For both measurement sets, the two-point technique was used, where first the optical power received at the end of a long fiber is measured and second, the fiber is broken at about 0.5 m from the launch end and the output power from the short length is measured. The ratio of the received power from the long fiber to that of the 0.5-m pigtail was used to calculate the transmission loss. The agreement between the two sets at 0.63 μm and the measurement repeatability are both about ± 0.2 dB for a 1-km fiber length.

4.1.1 Unpackaged fiber losses

Western Electric at Atlanta fabricated the 144 in-line coated optical fibers used for the Atlanta Experiment cable (12 ribbons each with 12 fibers). One hundred thirty-two fibers were coated with Alathon* 3172, and 12 were coated with Elvax* 460. The spectral loss of each unpackaged fiber was measured at seven different wavelengths between 0.63 and 1.05 μm. The lower curve in Fig. 3 is a plot of the mean spectral loss curve for the 144 unpackaged fibers measured, where the standard deviation at each wavelength is approximately 1 dB/km. At the Atlanta Experiment transmission wavelength of 0.82 μm (transmitter source was a GaAlAs laser operating at 0.82 μm), the mean unpackaged fiber loss was 4.7 dB/km.

4.1.2 ASR loss results

Twelve 1-km adhesive sandwich ribbons, each containing 12 fibers, were used in the Atlanta Experiment cable. The added loss due to packaging the fibers in the ribbon structure was measured using the He-Ne laser loss set. Due to the mechanical relaxation of the fibers within the ASR structure, the added packaging-induced microbending loss decreases with time after completion of ribbon manufacture. It has been found that the added loss due to ribboning relaxes to a quasi-steady-state minimum value within about 50 hours after the completion of ribboning. Table II shows the results for each of the 12 ASRs. For each ribbon listed in Table II, the manufactured ribbon length, fiber yield, and the mean added loss just after the completion of ribboning ($t = 0$ hours) and just before cable manufacture ($t > 200$ hours after ribboning) is shown. For the 137 transmitting fibers in these 12 ASRs, the mean added loss just before cable manufacture was 0.8 dB/km.

* Alathon and Elvax are ethylene-vinyl-acetate resins that are registered trademarks of E. I. DuPont de Nemours and Company.

Table II — ASR loss and yield results

Ribbon Designation	Manufactured Length (m)	Number of Transmitting Fibers	Mean Ribboning Added Loss (dB/km) $t = 0$	$t > 200$ Hours
ASR 281	1043	12	3.4	0.8
ASR 282	1054	12	6.0	1.1
ASR 284	1092	10	2.9	0.9
ASR 286	1067	12	2.8	0.6
ASR 287	1050	11	3.1	1.5
ASR 288	1092	10	3.1	0.4
ASR 290	1050	12	3.3	1.1
ASR 291	1146	12	3.3	0.7
ASR 292	1101	10	2.3	0.1
ASR 294	1047	12	3.9	0.8
ASR 295	1036	12	4.7	0.8
ASR 296	1081	12	4.1	1.3

4.1.3 Cable loss results

Using the 12 ribbons described, a 1023-m length of cable was manufactured for the Atlanta Experiment. The added loss due to cable manufacture was measured with the 1023-m length of cable wound loosely on a cable reel. The mean added loss due to cable manufacture was 0.5 dB/km for the 134 transmitting fibers in the cable (there were three fiber breaks during cabling). Figure 4 is a histogram of the total added losses due to ribbon and cable manufacture. The mean total packaging induced loss was +1.3 dB/km with a standard deviation of 1.3 dB/km for the 134 transmitting fibers in the 1023-m cable length. A 658-m section of this cable (with 138 transmitting fibers) was installed in a standard plastic underground duct network (see Fig. 5) at the Bell Laboratories/Western Electric Atlanta facility. The ducts terminate in a basement room and extend 150 m to a manhole, and then another 140 m to a second manhole. The lightguide cable was looped in the second manhole so that both ends could be terminated in the basement room. The remaining 365 m of cable not installed underground was cut off and used for mechanical and environmental tests described later in this paper. After completion of installation of the 658-m cable segment, the spectral loss was measured for each of the 138 transmitting fibers. The upper curve of Fig. 3 shows the mean spectral loss curve for the 138 fibers. Comparing the loss measurements between 0.63 and 1.05 μm for the unpackaged fibers and the installed-cable fibers (Fig. 3, lower and upper curve, respectively) indicates that the microbending loss is essentially independent of wavelength for this spectral region, as predicted.[8] These results also indicate that there was no measurable change in cabled fiber transmission loss due to installation. The mean installed-cable fiber loss at the source wavelength of 0.82 μm was 6.0 dB/km with a standard deviation of 1.9 dB/km.

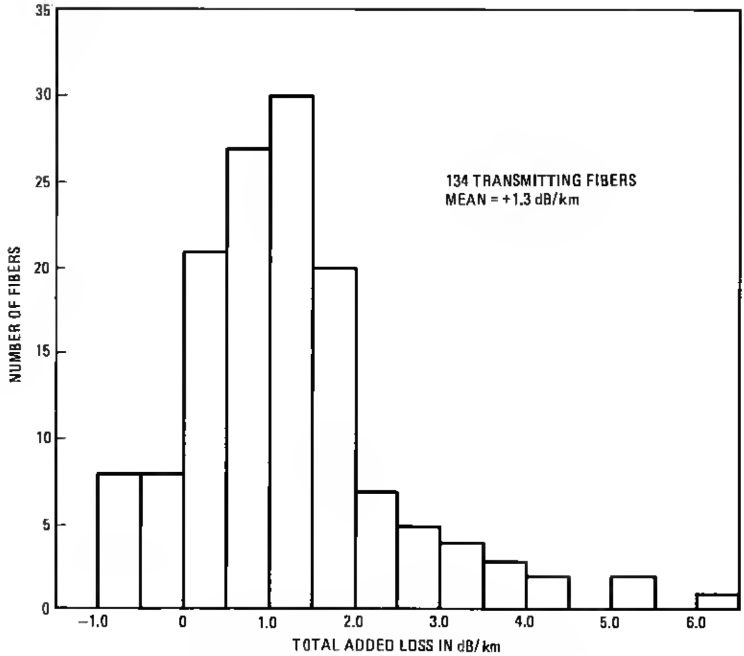

Fig. 4—Histogram of cabled fiber added losses.

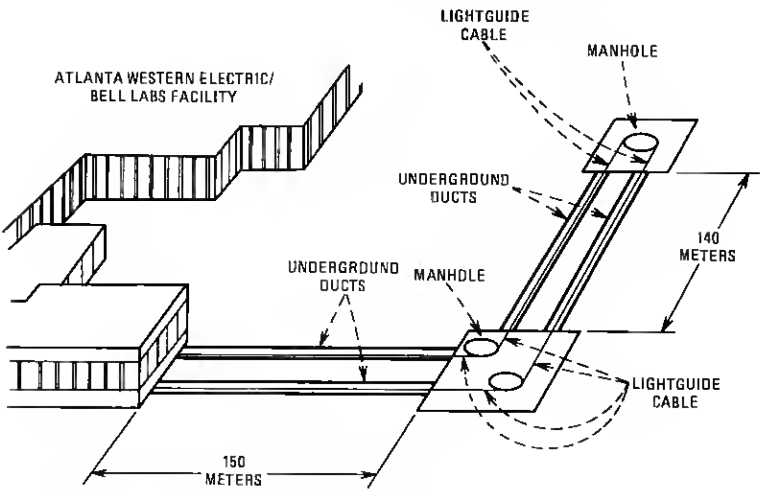

Fig. 5—Atlanta installation route.

4.2 Pulse delay distortion

Pulse spreading in a multimode optical fiber is reduced when the geometry (microbends) of the waveguide induces power mixing among the propagating modes (mode coupling).[12] In a waveguide with strong ran-

dom coupling among its guided modes, it has been predicted that for long enough lengths the width of the impulse response will increase witb the square root of the fiber length. Thus, the length dependence of pulse spreading for a particular fiber of a given length can vary between linear and square root, depending on the strength of tbe intermodal coupling.

The pulse delay distortion or pulse spreading characteristics of 72 of the 144 fibers in the experiment cable were obtained from impulse response measurements. The impulse response was measured at 0.82 μm using techniques and equipment described elsewhere.[13] The 3-dB bandwidth, i.e., the baseband frequency at which the Fourier transform of the fiber impulse response has decreased to $\frac{1}{2}$ of its dc loss value, will be used here as a figure of merit.

4.2.1 Unpackaged fiber bandwidths

The 72 unpackaged fibers characterized for the Atlanta Experiment cable varied in length between 1.1 and 2.3 km. Thus, in order to determine the effects of packaging on fiber pulse delay distortion, it is necessary to normalize the fiber pulse spreading results to a common length. Independent studies using fibers like those used for the Atlanta Experiment indicate that the unpackaged fiber pulse spreading is approximately linear with length (i.e., the coupling length was usually larger than 2.3 km). Using this approximation for the unpackaged fiber bandwidths, the mean, measured, unpackaged fiber-optical-3-dB-point bandwidth was 438 MHz for a 1-km length (with a standard deviation of 224 MHz).

4.2.2 ASR bandwidth results

The 72 unpackaged fibers measured for impulse response were all contained within six of the 12 ASRs used in the optical cable. The pulse spreading characteristics of the 68 of these 72 fibers that survived ribboning were remeasured after the completion of ribbon manufacture. Due to the fiber mode coupling induced by the ribbon package (as seen in Section 4.1.2), the ribboned fiber bandwidth is assumed to be inversely proportional to the square root of length (complete mode mixing). Since the six ribbons measured varied in length between 1043 and 1092 m, there is a minimum of ribboned fiber bandwidth data shifting required to normalize the data to a 1 km length. Using this length dependence assumption, the mean measured ribboned fiber bandwidth was 633 MHz for a 1-km length. However, it should be noted that the ribboned fiber bandwidths were usually measured right after the completion of ribbon manufacture. As mentioned in Section 4.1.2, the time decaying component of the ribboning added loss was not relaxed until about 50 hours after the completion of ribboning. Thus, the ribboned fiber bandwidths

measured are probably slightly high, since initially the fibers have additional mode mixing due to the unrelaxed ribboned fiber microbends.

4.2.3 Cable bandwidth results

For the 1023-m length of cable manufactured, 65 of the 72 fibers which had been measured in the unpackaged state survived ribbon and cable manufacture. The mean 3-dB point bandwidth measured for the 1023-m length of cabled fibers was 553 MHz (with a standard deviation of 309 MHz). For the 658-m length of installed cable, 68 of the 72 fibers were transmitting and had a mean 3-dB bandwidth of 690 MHz (with a standard deviation of 286 MHz). Using the measured bandwidth data for the 1023-m length of cabled fibers and the 658-m length of installed-cabled fibers, the 3-dB bandwidth was calculated to be proportional to (length)$^{-0.50\pm0.17}$. This result provides excellent agreement with previous predictions of square-root-of-length dependence for complete mode mixing.[14] Using this measured square-root-of-length dependence, the mean cabled fiber bandwidth normalized to a 1-km length was calculated to be 559 MHz. Thus, the mean 3-dB bandwidth increase in going from unpackaged to cabled fibers was 121 MHz (with a standard deviation of 249 MHz) for a 1-km length. However, this increase in bandwidth was accompanied by a mean increase in loss of 1.3 dB/km.

V. ENVIRONMENTAL PERFORMANCE

Unless special precautions are taken during storage, shipment, and installation of cables, they may encounter a large range of temperature exposures. Dimensional changes within the optical fiber cable structure, due both to linear thermal expansion of materials and polymeric shrinkback, can result in variations in the optical transmission properties of the fiber, thus possibly impairing system performance.

To evaluate how temperature variations affect the optical performance of the Atlanta Experiment fiber optic cable, a 156.4-m section was installed in a thermally insulated, underground, temperature-controlled, copper duct. The temperature of this duct can be controlled to about $\pm 1°F$ over the range of $+30°F$ to $+150°F$. Ribbons at one end of the cable were spliced together in pairs with six ribbon splices,[15] thus providing 72 fiber links, each 312.8 m in length. Four of these 312.8-m fiber links were spliced together at the other cable end using three low-loss, loose-tube, individual fiber splices,[16] thus forming a single 1251.2-m cabled fiber link. This 1251.2-m link was used to determine environmental effects on loss and pulse delay distortion at 0.82 μm. Forty of the 312.8-m cabled fiber links were each measured for the environmental effects on the loss at 0.63 μm.

During the environmental tests at exposure temperatures above

+70°F, the cahle was allowed to stahilize for 72 hours hefore measurements were made. Twenty-four-hour exposure was assumed sufficient at low temperatures. To better ascertain the nature (reversihle or not) and magnitude of the effect of the temperature exposure, the cahle was always returned to +70°F before any suhsequent temperature exposure.

Figure 6 shows a plot of the sensitivity of cahle loss to thermal history measured at 0.63 μm for the forty 312.8-m fiher links. Figure 7 shows a plot of the sensitivity of cahle handwidth to thermal history, measured at 0.82 μm, for the single 1251.2-m fiher link. Correlation of the data measured for the 0.82-μm loss and handwidth changes induced hy the +30°F to +150°F exposure temperatures shows that the 3-dB handwidth increased hy 9.9 ± 0.5 MHz (3.0 percent) for a loss increase of 1.0 dB (6.2 percent), with a coefficient of correlation of 0.86. Moreover, there was essentially unity correlation hetween the 0.63-μm and 0.82-μm loss changes, suggesting that these temperature-induced microbending loss variations are essentially linear with length and independent of wavelength over this wavelength range, as expected.[8] The environmental results presented here clearly show that the cabled fiher loss and

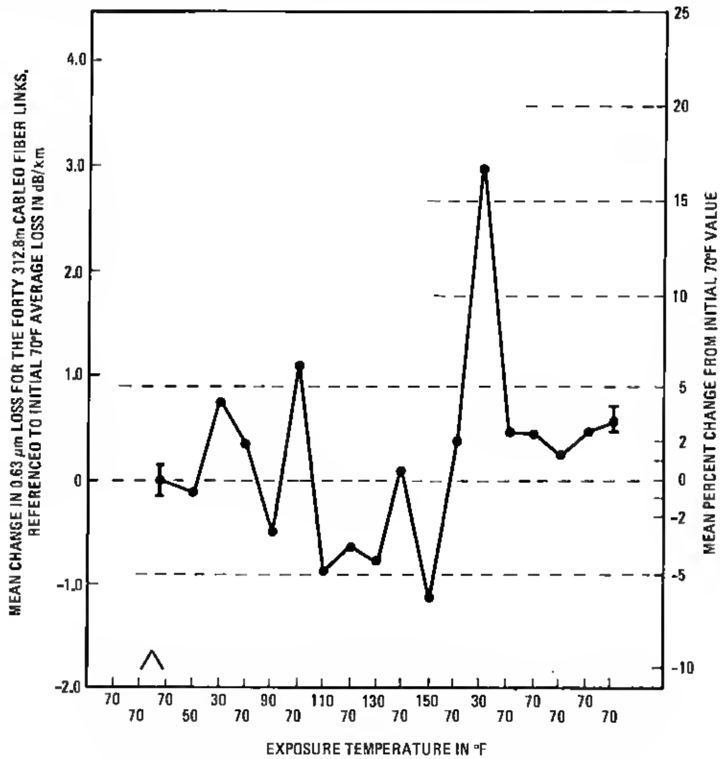

Fig. 6—Change in 0.63-μm loss vs. exposure temperature.

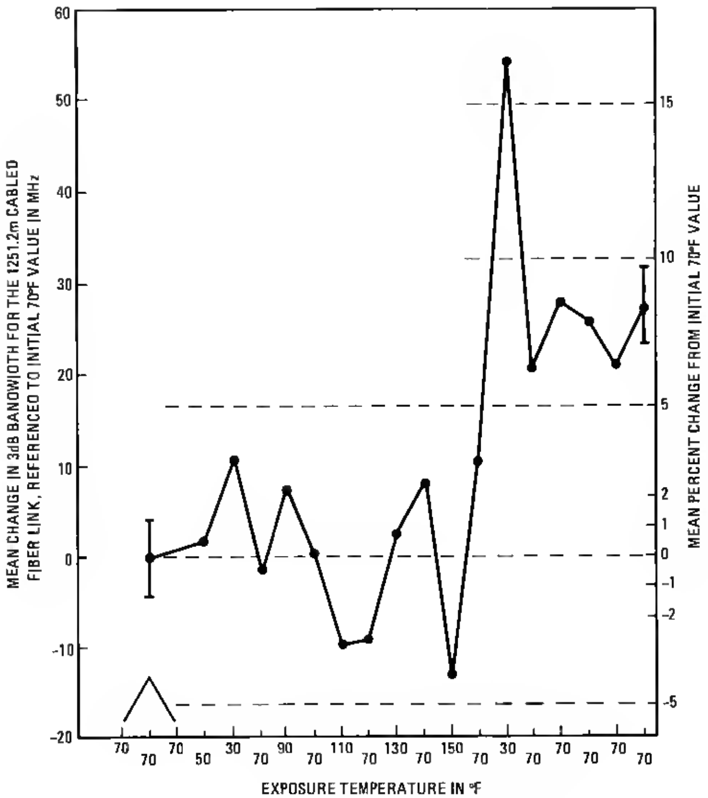

Fig. 7—Change in 0.82-μm bandwidth vs. exposure temperature.

bandwidth changes for this cable depend not only on cable exposure temperature but on thermal history as well.

Design modifications of the "Atlanta type" optical cable are in progress, with the goal of reducing temperature-induced loss variations to less than 0.5 dB/km over a temperature range from at least −20°F to +150°F.

VI. MECHANICAL PERFORMANCE

Mechanical tests were conducted on a number of segments of the Atlanta Experiment cable. The cable segments were subjected to both tensile and bending tests. Figure 8 shows a typical curve obtained for cabled fiber survival versus cable load and strain. No fiber breaks occurred until the cable load exceeded 1779 Newtons, with more than 85 percent of the fibers still surviving at a load of 4448 N. Also, cable reverse bends, which consisted of a 90-degree bend with a 12.5-cm radius followed by a second 90-degree bend of 12.5-cm radius in the opposite di-

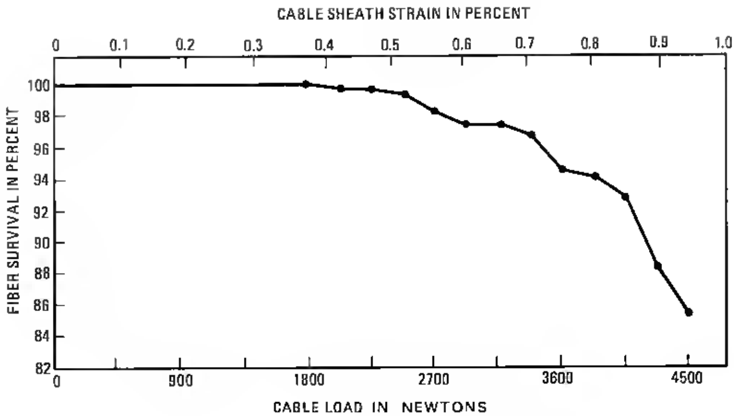

Fig. 8—Percent fiber survival versus cable load.

rection, caused no fiber breaks or cable degradation. These results provide further proof that small, ruggedized, lightweight (the Atlanta cable weighs only 934 N/km) fiber optic cables can be designed to package hundreds of high-capacity lightguides.

VII. CONCLUSIONS

The design and characterization of the optical fiber ribbons and cable used in the Atlanta Experiment have been described. The cable performed well, and results of the optical cable tests indicate that high performance, large-capacity, optical-fiber cables are feasible. The successful integration of this optical cable with the other necessary fiber-optic transmission system components is described in companion papers in this B.S.T.J. issue. This optical cable design was the stepping-stone to the installation of optical fiber cables for the Bell System's Chicago Lightwave Communications Project.[17] In the Chicago Project, the optical cables are of the same design, but contain only a two-ribbon core (24 fibers), and are being evaluated under actual live customer traffic.

As a result of the design and evaluation of the Atlanta Experiment optical cable, new designs and material changes are being investigated. The goal of these efforts is to improve performance and increase the compatibility of the cable with real-world handling and environmental conditions.

VIII. ACKNOWLEDGMENTS

The successful completion of the Atlanta Experiment optical cable is due to the efforts of many individuals at Bell Laboratories and Western Electric. In particular, we would like to acknowledge the efforts of W. P. Maxey in cable manufacture, W. L. Parham in ribbon manufacture, and L. Wilson in optical characterization.

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